IEEE 802.11 OPTIMAL PERFORMANCES: RTS/CTS MECHANISM VS. BASIC ACCESS*

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Abstract - In this paper we address the throughput analysis of high-speed IEEE 802.11b WLANs from both an analytical and simulative perspective. Specifically, we derive the throughput formula for the *RTS/CTS Access* method of the p-persistent IEEE 802.11b MAC protocol. The accuracy of the proposed model is exhaustively validated via simulative results. By exploiting our formulas, we derive the theoretical upper bound for the throughput performance of the IEEE 802.11b protocol. Our analytical and simulative results indicated that the RTS/CTS mechanism produces very limited advantages in the standard IEEE 802.11 networks with respect to the basic access when no hidden stations are present. Finally, we extend a distributed backoff-tuning strategy firstly proposed for the basic access method, and we validate its effectiveness to closely approach the throughput limit of the IEEE 802.11b protocol.

Keywords – IEEE 802.11b, MAC protocol, RTS/CTS mechanism, performance evaluation, performance modeling.

I. INTRODUCTION

At the end of the 1999 a new high-speed standard for wireless LAN was ratified by the IEEE 802.11 standards body, the IEEE 802.11b [8]. This standard overtakes the original 1 and 2 Mbs direct sequence physical layer transmission standard [7] to reach the 11 Mbs. This bandwidth increase is mainly due to more sophisticated coding techniques, rather than to enhancements of the MAC protocol. Even though the channel bandwidth is significantly increased with the IEEE 802.11b standard, the study of WLANs has to still concentrate on the bandwidth consumption, since the overheads introduced by both the access scheme and the physical layer are very critical in high-speed channels.

In this work we analyze the throughput performance that is achievable with the IEEE 802.11b protocol from both an analytical and simulative perspective. Our study takes into account all the overheads introduced by both the MAC protocol and the physical layer, in order to precisely evaluate the ability of the IEEE 802.11b standard to effectively utilize the increased channel bandwidth. Several works (see [9]) have investigated via simulation the IEEE 802.11 protocol. At the same time, accurate analytical models have been proposed ([1], [4], [5], [6]) to study the throughput of the IEEE 802.11 MAC protocol. As already shown in literature, a p-persistent IEEE 802.11 protocol [4], i.e., an IEEE 802.11 protocol where the backoff interval is sampled from a geometric distribution with parameter p, closely approximates (from a throughput standpoint) the standard protocol that operates with the same average backoff window size. However, in [4] and [5] only the Basic Access method is analyzed, whereas in [1] the RTS/CTS access method is studied with the simplified assumptions of *i)* fixed length messages and *ii)* not co-existence of RTS/CTS and Basic Access method. In this paper we extend these analytical results, since we derive the throughput formula for the IEEE 802.11b protocol by assuming a general message-length distribution and by allowing the co-existence of RTS/CTS and Basic Access method. The accuracy of the proposed model is exhaustively validated via simulative results.

The RTS/CTS access method was introduced in the standard mainly to obtain a better behavior in two situations: *i*) transmission of long messages and *ii*) presence of hidden stations. In this work we don't address the hidden station issue (the interested reader can find in [10] simulative results showing the inability of RTS/CTS mechanism to resolve the hidden station problem), but we focus on evaluating the efficiency of the basic access and RTS/CTS mechanism in ideal conditions (no channel errors, no hidden stations) to identify the theoretical limits of this technology. Specifically, by exploiting our formulas we quantify the theoretical upper bound for the channel utilization. Hereafter, the maximum value of the channel utilization achievable by the MAC protocol is referred to as *protocol capacity*. The results presented in this paper indicate that the Basic Access method of the IEEE 802.11b protocol (if adequately tuned) outperforms the RTS/CTS access method also when most of the traffic is constituted by long messages. Finally, we show that the theoretical throughput limit can be obtained by tuning the backoff window size according to feedback information from the channel status. To this end, we extend a distributed backoff-tuning strategy based on a very simple estimation of the network status firstly proposed for the basic access method [2], and we validate its effectiveness to closely approach the throughput limit of the IEEE 802.11b protocol.

The paper is organized as follow. In section II we derive and validate the throughput formula for the IEEE 802.11b MAC protocol. In section III we propose and analyze a distributed

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feedback-based backoff-tuning strategy to approach the throughput limit. In section IV final remarks are drawn.

II. PROTOCOL MODEL AND ANALYSIS

For a complete and detailed description of the IEEE 802.11b MAC protocol, refer to the standard ([7], [8]). Let us introduce the notation adopted in the following analysis. Let PHY_{hdr} be the *physical header* that precedes the transmission of a MAC frame and MAC_{hdr} be the *MAC header* added to the *data payload*. Hence, $H = PHY_{hdr} + MAC_{hdr}$ is the total overhead we have to add to the data payload. Hereafter, the data payload length will be expressed in bytes. We denote with t_x the time occupied by the transmission of the X-type event. Specifically, t_B, t_H t_{RTS}, t_{CTS} and t_{ACK} are the time needed to transmit a byte, the overhead H, the RTS, CTS and ACK message. Finally, τ is the maximum propagation delay over the wireless channel.

A. A closed formula for the throughput in a p-persistent IEEE 802.11b protocol

Let us consider a M-stations network where each station adopts the p-persistent IEEE 802.11b protocol. The p-persistent IEEE 802.11b protocol differs from the standard only in the selection of the backoff interval. At the beginning of an empty slot, a station transmits (in that slot) with a probability p, while the transmission differs with a probability $1-p$, and then repeats the procedure at the next empty slot. (on the other hand, in the standard protocol, a station transmits in the empty slot uniformly selected inside the current backoff window). In the following discussion we assume that: *i)* all the stations operates in *saturation conditions*, i.e., they have always a message waiting to be transmitted and *ii)* the message lengths are random variables identically and independently distributed. According to assumption *ii)* above, and considering the p-persistent protocol behavior, we can assess that all the processes that define the channel occupancy pattern are regenerative with respect to the sequence of time instants corresponding to the completion of transmission attempts. Using the same renewal theory arguments adopted in [5], it immediately follows that the channel utilization formula is:

$$\rho = \frac{E[L]t_B p_1}{t_{slot} p_0 + E[Succ]p_1 + \{E[Coll \mid Coll] + \tau + EIFS\}\{1 - p_0 - p_1\}} \tag{1}$$

where:

- $E[L]$ is the average message length expressed in bytes;
- $E[Succ]$ is the average duration of a successful transmission, given a transmission attempt;
- $E[Coll \mid Coll]$ is the average duration of a collision, given that a collision occurs;
- $p_0 = P\{N_{tr} = 0\} = (1-p)^M$, $p_1 = P\{N_{tr} = 1\} = Mp(1-p)^{M-1}$ (N_{tr} is the number of transmitting stations at the beginning of an empty slot).

The unknown quantities in (1) are derived in Lemma 1.

LEMMA 1. In a network with M active stations, by assuming that each message with data payload greater than l_{RTS} bytes is transmitted according to the RTS/CTS access method otherwise it is transmitted according to the Basic Access method, it follows:

$$\begin{aligned} E[Succ] = {} & (2\tau + t_B + E[L]t_B + DIFS + t_{ACK} + SIFS) + \\ & [1 - F(l_{RTS})](2\tau + 2 + SIFS + t_{RTS} + t_{CTS}) \end{aligned} \tag{2}$$

$$\begin{aligned} & E[Coll \mid Coll] = \\ & t_H + \frac{t_{RTS} - t_H}{1 - p_0 - p_1}\{[1 - F(l_{RTS})]^M - [p_0 - (1 - F(l_{RTS}))p_1]\} + \\ & \frac{t_B}{1 - p_0 - p_1} \sum_{i=1}^{\min\{l_{MAX}, l_{RTS}\}} i\{[1 - (F(l_{RTS}) - F(i))p]^M - \\ & [1 - (F(l_{RTS}) - F(i-1))p]^M - (F(i) - F(i-1))p_1\} \end{aligned} \tag{3}$$

where $F(i)$ is the probability that the message length is less or equal to i bytes, and l_{MAX} is the maximum data payload length allowed by the protocol.

Proof. Omitted due to the space constraints.

It is worth pointing out that the basic access method is a special case of the RTS/CTS access method. The $E[Succ]$ and $E[Coll \mid Coll]$ formulas for the basic access method (see [4]) are straightforwardly derived by lemma 1 when $l_{RTS} > l_{MAX}$. Therefore, the throughput formula (1) is suitable for the analysis of both access methods.

B. Model validation

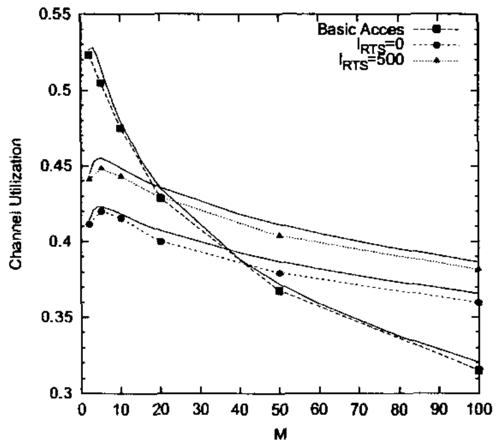
To validate the proposed model, we have compared results derived by (1) with those obtained via a simulator of the IEEE 802.11b protocol. To consider a realistic scenario for the traffic distribution, throughout this work we have adopted a bimodal message-length distribution where the data payload is 40 bytes long with probability q_0, and 1500 bytes long with probability $1-q_0$.

Table 1. DSSS system parameters

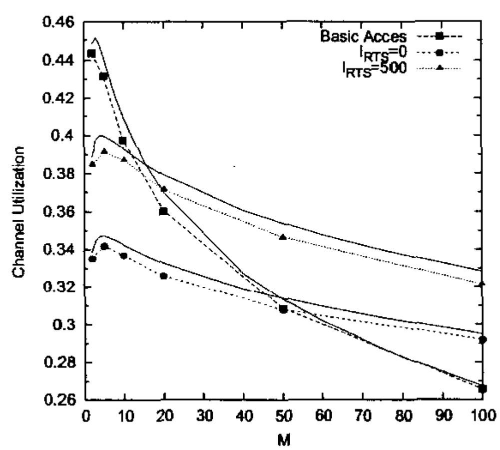
τ	t_{slot}	$SIFS$	$DIFS$	$EIFS$	MAC_{hdr}
1 μs	20 μs	10 μs	50 μs	364 μs	272 *bits*
PHY_{hdr}	t_{ack}	t_{rts}	t_{CTS}	cw_{MIN}	cw_{MAX}
192 μs	202 μs	214 μs	202 μs	31 t_{slot}	1023 t_{slot}

It is worth reminding that the correspondence of p-persistent IEEE 802.11b protocol with the standard one is guaranteed when the p value is chosen in such a way to have the same average backoff window size in both the protocols. In [4] it was defined a recursive algorithm to evaluate the average backoff window size of the IEEE 802.11 protocol. We use the same algorithm to derive the average backoff window size of the IEEE 802.11b protocol, and then the equivalent p value. The parameters' setting used to obtain numerical results for both the analytical and simulation study, are listed in Table 1.

The system parameters are those specified for the 11 Mbs direct sequence spread spectrum (DSSS) physical layer [8].



(a) $q_0 = 0.3$



(b) $q_0 = 0.5$

Figure 1. Channel utilization: analysis against simulation

Figures 1(a) and 1(b) show the comparison between the channel utilization of the IEEE 802.11b protocol as evaluated via simulation, with the channel utilization measured from (1), when the number M of stations is in the range [2...100]. Figures 1(a) and 1(b) consider the traffic scenarios where the small messages are either the 30 percent ($q_0 = 0.3$) or the 50 percent ($q_0 = 0.5$) of the total traffic, whereas (the scenario where only long messages are transmitted ($q_0 = 0$) provides similar results, see also [1]). We have studied the case when: *i)* all the messages are transmitted with the RTS/CTS mechanism ($l_{RTS} = 0$), *ii)* only the long messages are transmitted with the RTS/CTS mechanism ($l_{RTS} = 500$), and *iii)* only the Basic Access method is adopted. The figures show that the model is very accurate: analytical results (black lines) are less than 1% above the measured performances in all the analyzed configurations.

From the figures we can draw further interesting observations. The numerical results show that, for a given number M of stations, the throughput increases as the average message length increases. Furthermore, the selection of the l_{RTS} threshold is critical for the system performances, and the best choice is to apply the RTS/CTS access method only for the long messages. Finally, the Basic Access method is much more affected by the number of stations in the network than the RTS/CTS access method, and its performances rapidly decrease when M increases. Indeed, the RTS/CTS access method outperforms the Basic Access method for large M values.

III. THROUGHPUT MAXIMIZATION

As it appears from (1), $\rho = f(p, M, l_0, l_1, q_0)$. The protocol capacity, say ρ_{MAX}, is obtained by finding the p value, say p_{opt}, that maximizes Equation (1). The ρ_{MAX} and p_{opt} values have been numerically evaluated in a wide set of network and traffic configurations. Due to the correspondence (from the throughput standpoint) between the standard IEEE 802.11b protocol and the p-persistent one, the ρ_{MAX} value represents also a throughput limit for tuning the IEEE 802.11 protocol. The p_{opt} will be a function of the M parameter and of the message length distribution. However, the M value is unknown and its estimation at run-time could result expensive, difficult to obtain and subject to significant errors, especially in high contention situations [5]. Therefore, the Equation (1) can be adopted to derive the optimal capacity state in an off-line analysis, but it would be convenient to derive a simpler relationship to provide an approximation of the p_{opt} value that guarantees a *quasi-optimal* capacity state.

A. A balancing equation to derive a quasi-optimal capacity state

In [4], the balance between the time wasted in collisions and the idle time is identified as the condition to determine a quasi-optimal capacity state in a *p-persistent* IEEE 802.11 protocol where the message length was sampled from a geometric distribution. In this paper we re-propose to adopt a similar balancing equation. The small modification is introduced to take in consideration the protocol overheads.

Specifically, we consider as optimal operating point the p value for which the following relationship hold:

$$E[Idle\_p] = \{E[Coll \mid Coll] + \tau + EIFS\} \frac{1 - p_0 - p_1}{1 - p_0} , \quad (4)$$

where $E[Idle\_p]$ is the average time a station spends listening the channel before a transmission attempts, and the r.h.s. of (4) is the average time a station spends in collisions and waiting for the acknowledgment given that a transmission attempt occurs (the second term in the r.h.s. of (4) is the collision probability given a transmission attempt [4]). For the $E[Idle\_p]$ expression see [4]. Hereafter, for brevity of notation, we will refer to the l.h.s. of (4) as $\bar{I}$, and to the r.h.s. as $\bar{C}$.

Equation (4) was proposed in previous papers using heuristic considerations. Specifically, it is straightforward to observe that $\bar{I}$ is a decreasing function of the p value, whereas $\bar{C}$ is an increasing function of the p value. Therefore, (4) suggests that a quasi-optimal capacity state is achieved when each station behaves in such a way to balance these two conflicting costs.

The precision of the capacity approximation derived by (4) is studied in Tables 2 to 4. Specifically, we compare the ρ_{MAX} value, numerically evaluated by maximizing Equation (1), with the channel utilization, say ρ_{EXT}, measured substituting in (1) the p value that satisfies (4).

Table 2. Accuracy of Equation (4) for $q_0 = 0.3$

M	Capacity			Quasi-optimal Capacity		
	Basic Access	$l_{RTS}=0$	$l_{RTS}=500$	Basic Access	$l_{RTS}=0$	$l_{RTS}=500$
2	0.53978	0.43126	0.46428	0.53978	0.43126	0.46428
10	0.51593	0.42144	0.45274	0.51591	0.42142	0.45271
100	0.51153	0.41957	0.45054	0.51150	0.41954	0.45050

Table 3. Accuracy of Equation (4) for $q_0 = 0.5$

M	Capacity			Quasi-optimal Capacity		
	Basic Access	$l_{RTS}=0$	$l_{RTS}=500$	Basic Access	$l_{RTS}=0$	$l_{RTS}=500$
2	0.46331	0.35475	0.40998	0.46331	0.35475	0.40998
10	0.44035	0.34561	0.39755	0.44032	0.34559	0.39752
100	0.43613	0.34388	0.39520	0.43610	0.34385	0.39516

Table 4. Accuracy of Equation (4) for $q_0 = 0$

M	Capacity		Quasi-optimal Capacity	
	Basic Access	$l_{RTS}=0$	Basic Access	$l_{RTS}=0$
2	0.62170	0.51715	0.62170	0.51715
10	0.59859	0.50711	0.59857	0.50709
100	0.59429	0.50519	0.59427	0.50516

The numerical results listed in the tables show that the balancing equation is amazingly precise: it provides a capacity approximation with an error always lower than 0.1% in all the configurations analyzed. Furthermore, the capacity analysis provides a very unexpected and interesting result: in all the configurations analyzed (even the case of fixed message length of 1500 bytes), the protocol capacity of the Basic Access method is greater than the one of the RTS/CTS access method.

B. A feedback-based backoff-tuning strategy to approach the protocol capacity

In [2] we have designed a policy to dynamically tune the backoff in order to approach the protocol capacity. Below, following the same line of reasoning, we extend it to our case. Equation (4) provides a robust criterion to afford, at run-time, the channel-utilization maximization. Specifically, each station, by exploiting the carrier sensing mechanism, is able to distinguish the idle periods by collisions and successful transmissions. Hence, we can assume that at the end of the n-th transmission attempt, each station knows its transmission probability used for the n-th transmission attempt, say p_n, an estimate of the average time spent listening the channel, say $\bar{I}_n$, and an estimate of the average collision length, say (included the overhead EIFS), say $\bar{C}_n$. If $p_n \neq p_{opt}$, (4) does not hold and $\bar{I}_n \neq \bar{C}_n$. For the (n+1)th transmission attempt, our control strategy searches a new transmission probability p_{n+1} such as to have $\bar{I}_{n+1} = \bar{C}_{n+1}$, i.e., to balance (in the future) the time spent during idle periods and collisions. Obviously, if $\bar{I}_{n+1} > \bar{C}_{n+1}$ we should increase the p value, otherwise we should decrease it. Hence, the new transmission probability p_{n+1} can be expressed as a function of p_n and an unknown quantity x, such that $p_{n+1} = p_n(1+x)$. To derive the unknown quantity x, we exploit Equation (4) and approximated formulas for $E[Idle\_p]$ and $E[Coll \mid Coll]$ (see [2] for the details about $E[Idle\_p]$ and $E[Coll \mid Coll]$ approximations). Figure 2 summarizes the algorithm's steps.

Begin

1: $Idle\_p_n$ = duration od the n-th idle period;

2: $Coll_n$ = duration of the n-th collision;

3: $\bar{I}_{n+1} = \alpha \cdot \bar{I}_n + (1-\alpha) \cdot (idle\_p_n + \tau + DIFS)$;

4: $\begin{cases} \bar{C}_{n+1} = \alpha \cdot \bar{C}_n + (1-\alpha) \cdot (Coll_n + \tau + EIFS) & \text{if } Coll_n > 0 \\ \bar{C}_{n+1} = \alpha \cdot \bar{C}_n & \text{if } Coll_n = 0 \end{cases}$;

5: $p_{new} = p_n \cdot \dfrac{\sqrt{1 + 4(1 + \bar{I}_n)\bar{C}_n} - 1}{2\bar{C}_n - 1}$;

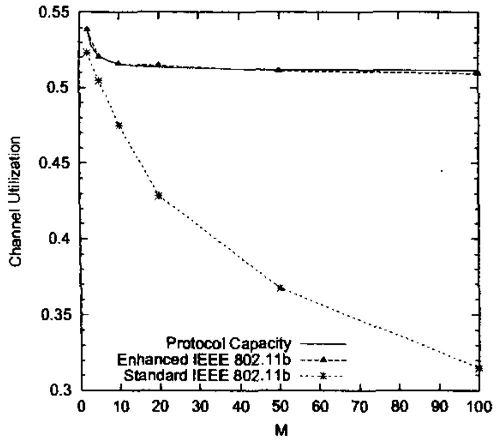
6: $p_{n+1} = \alpha \cdot p_n + (1-\alpha) \cdot p_{new}$;

End

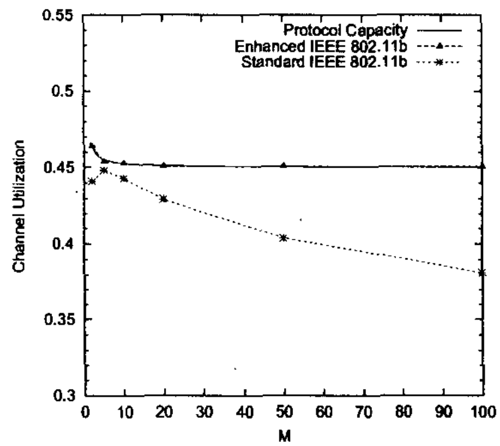
Figure 2. Algorithm's operations

It is worth pointing out that to identify the optimal p value is equivalent to identify, in the standard protocol, the optimal average backoff window size. This means that the procedure analyzed in the following to tune the p-persistent

IEEE 802.11b protocol, can be exploited in an IEEE 802.11b network to select, for a given contention level, the appropriate size of the backoff window.



(a) $l_{RTS} = 0$



(b) $l_{RTS} = 500$

Figure 3. Enhanced IEEE 802.11 capacity for $q_0 = 0.3$

The effectiveness of the proposed feedback-based backoff-tuning strategy has been investigated through simulation results. To this end we run simulation experiments to evaluate the channel utilization of the Enhanced IEEE 802.11b protocol. Specifically, Figures 3(a) and 3(b) compare the channel utilization of the standard protocol and of the enhanced one against the theoretical upper bound when the number M of stations is in the range $[2...100]$. The curves refer to the $q_0 = 0.3$ case, but we have obtained similar results with both $q_0 = 0.5$ and $q_0 = 0$, and are not reported here due to the space constraints. The results related to the basic access are very similar and are not reported here (for more details see [2])

The numerical results show that the Enhanced IEEE 802.11b approaches very closely the throughput limit in all the configurations analyzed.

IV. CONCLUSIONS

The main contributions of this work are: *i)* the derivation and validation of a closed formula for the throughput of IEEE 802.11b protocol adopting the RTS/CTS mechanism and using a general message-length distribution; *ii)* the validation of a balancing equation that defines the condition to attain a quasi-optimal capacity state. Our analytical and simulative results indicate that the RTS/CTS mechanism has very limited utility also when the system is ideal. In fact, only for high values of the network population (grater than 20) the RTS/CTS mechanism slightly enhances the basic access, which has very good performance. In the paper we have presented a strategy to dynamically tune the backoff that drives the network very close to the theoretical throughput limit. Our results indicate that the basic access has a higher theoretical throughput limit than the RTS/CTS.

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